

Biofuel Development from Cellulosic Sources

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Key Concepts

- Renewable energy sources such as solar power, wind power, geothermal power, and bioenergy will improve energy sustainability and reduce environmental impacts associated with human energy use.
- Two types of bioenergy feedstocks exist: first-generation feedstocks that are derived from food crops and advanced feedstocks that are derived from nonfood plants. Advanced feedstocks include cellulosic bioenergy crops such as herbaceous perennial grasses, short-rotation woody crops, and annual crop residues.
- Due to the complex structure of lignocellulosic plant material, cellulosic bioenergy feedstocks are generally more difficult to process into liquid fuels than food crops. However, a variety of both thermochemical and biochemical conversion technologies exist or are being developed to improve the transformation of cellulosic biomass into alternative energy sources.
- Although cellulosic bioenergy crops are thought to have fewer adverse effects on natural ecosystems than first-generation bioenergy crops, the extent of their impact is determined by the bioenergy species grown, how the crop is managed, and the type of land-use changes associated with the cultivation of the bioenergy crop.
- Land-use changes associated with cellulosic bioenergy crop production can be direct (land-use change occurs directly for cultivating bioenergy feedstocks) or indirect (land-use change occurs on land not used for bioenergy production due to the displacement of land used for food crop production), and each can have different impacts on the environment.
- The cultivation of cellulosic bioenergy crops produces fewer greenhouse gas emissions than first-generation bioenergy crops. Highly productive cellulosic bioenergy crops may also sequester more atmospheric carbon dioxide, which can reduce greenhouse gas emissions associated with bioenergy land-use changes.
- Cellulosic bioenergy crops have the potential to reduce soil erosion, rehabilitate degraded soil, increase soil organic carbon (SOC), and counteract SOC losses due to food crop and first-generation bioenergy feedstock cultivation.
- Cellulosic bioenergy feedstocks generally use water and nutrients more efficiently than first-generation bioenergy crops, which may decrease irrigation and fertilization requirements for bioenergy feedstock production. This can benefit aquatic systems by reducing water-use and nutrient runoff.
- Land-use changes resulting in habitat loss and habitat fragmentation can impact native wildlife species. However, cellulosic biomass feedstocks have the potential to provide habitat for insects, small birds, and mammals if landscape heterogeneity is maintained.

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- Some perennial biomass feedstocks have the potential to become invasive in ecosystems and also accelerate the spread of pathogens and other invasive species when grown in monocultures.

Introduction

Nonrenewable natural resources such as coal, petroleum, and natural gas have long been exploited for energy consumption due to their historic relative abundance, versatility, transportability, and low cost. However, global reserves of these raw materials are finite and are rapidly decreasing as global demand for energy increases. Extracting and using these energy sources can also have many negative environmental consequences. For example, fossil fuel combustion releases geologically stored carbon and other pollutants into the atmosphere, including greenhouse gases that cause climate change, indirectly damage ozone, contribute to acid deposition, and cause ocean acidification (Schlesinger and Bernhardt 2013). The physical exploitation of these fuels also damages the earth's surface layers, contaminates watersheds, and occasionally results in accidental marine contamination. Overall, the depletion of fossil fuel reserves, increasing global demand for energy, and the adverse environmental impacts associated with liquid and solid fossil fuel exploitation have highlighted the need to decrease dependence on nonrenewable fuel sources and have stimulated global interest in replacing fossil energy with alternative, sustainable solutions for future energy consumption.

Renewable energy technologies such as solar power, wind power, geothermal power, and bioenergy have the potential to improve energy sustainability and reduce the environmental consequences associated with human energy consumption. Bioenergy, in particular, is a renewable energy source that is primarily derived from plant material and is used to produce various energy products via direct combustion or chemical processing. Bioenergy feedstocks (i.e., biomass) include dedicated energy crops, agricultural food crops and residues, oil products, and other organic waste materials. Depending on the raw material and conversion pathway used, these feedstocks can produce an array of energy products ranging from liquid biofuels (e.g., biodiesel and bioethanol) to heat and electricity. Bioenergy is widely regarded as a viable alternative energy source because it has the potential to offer a broad range of socioeconomic and ecological benefits. In addition to reducing reliance on traditional fossil fuels, biomass production and biofuel processing can create employment opportunities, particularly in rural areas, and provide energy independence in both developing and industrialized countries. Bioenergy may also reduce carbon emissions because bioenergy crops sequester atmospheric carbon dioxide as they grow and because biomass combustion only releases as much carbon dioxide into the atmosphere as plant growth has sequestered. Therefore, bioenergy has the potential to become an economically beneficial and environmentally sustainable solution to the present energy crisis.

Although bioenergy is versatile and can provide various solutions to current energy concerns, biomass is predominantly used in the developed world for biodiesel or bioethanol to replace petroleum transportation fuels. These fuels are of particular interest because they do not require major modifications to current transportation systems and can be easily mixed with fossil petroleum as fuel additives. Presently, biofuels are produced from “first-generation” (i.e., conventional) sources that are also used commercially as food crops. For instance, bioethanol is fermented from sugar sources such as corn grain (*Zea mays* L.) or sugar cane (*Saccharum officinarum* L.), while biodiesel is processed from oil crops such as soybean (*Glycine max*, L.) and rapeseed (*Brassica napus* L.). The technologies used to produce first-generation biofuels are currently well established,

and although biofuel additives/substitutes are not yet major energy sources in the transportation sector, their production is now commercial. Biofuels do have the potential to contribute significantly to the transportation sector in the future; however, first-generation biofuels also raise several economic and environmental concerns (Williams et al. 2009). For example, first-generation bioenergy crops place increased pressure on the food industry because they compete with land used for food production and/or directly reduce the availability of feedstocks used commercially for food. These crops also require extensive water, fertilizer, and pesticide inputs, and their cultivation is associated with soil erosion, air and water pollution, and biodiversity losses as marginal grasslands and pastures are put into cultivation. Finally, the energy use associated with crop production and biofuel conversion processes may produce carbon emissions that do not result in a beneficial carbon balance. These disadvantages suggest that first-generation bioenergy crops may have long-term environmental costs and have thus generated an interest in developing bioenergy from alternative sources.

Biofuels produced from nonfood materials (i.e., “advanced” biofuels) have the potential to mitigate many of these concerns. Advanced biofuels are typically produced from cellulosic feedstocks, including dedicated herbaceous bioenergy crops (e.g., perennial C₄ grasses such as switchgrass or *Miscanthus x giganteus*), short rotation woody crops (e.g., hybrid poplar, willow), annual crop residues (e.g., corn stover), forest residues (e.g., commercial logging residues), and municipal solid waste (e.g., tree trimmings and paper products). These materials are generally cheap and abundant and have less potential to strain the food industry because they are derived from nonfood sources. Dedicated bioenergy crops, in particular, can produce high yields with relatively little water and nutrient inputs. When managed correctly, these crops can also have fewer adverse effects on the environment than first-generation crops (Howarth and Bringezu 2009). Like first-generation biomass feedstocks, cellulosic feedstocks can be burned directly for heat or can be chemically converted to liquid biofuels. However, cellulosic materials are more difficult to process than traditional biomass feedstocks and the additional conversion steps associated with breaking down lignocellulose into fermentable sugars render advanced biofuels cost-ineffective at the present (Carroll and Somerville 2009). If cellulosic biofuels were cost-competitive with first-generation biofuels, though, they could potentially become a commercially viable alternative energy source in the future. The costs and benefits of bioenergy production, as well as the environmental impacts associated with bioenergy production, will therefore be important to consider when evaluating the future sustainability of cellulosic biofuels.

The goal of this chapter is to provide an overview of biofuel production from cellulosic materials and to explore the environmental impacts associated with these processes. First, the various feedstocks, conversion technologies, and fuel products associated with cellulosic bioenergy production will be described in detail. The challenges of producing these biofuels will also be highlighted. Second, the potential impacts of cellulosic biofuel production on natural ecosystems will be explored. This section will provide an in-depth discussion of how different land-use changes and management practices associated with cellulosic biofuel production can affect greenhouse gas emissions, habitat fragmentation, biodiversity, soil properties, and water quality. Ultimately, this chapter will explore the advantages and disadvantages of advanced cellulosic biofuels as an alternative fuel source, particularly with respect to production efficacy and environmental impacts.

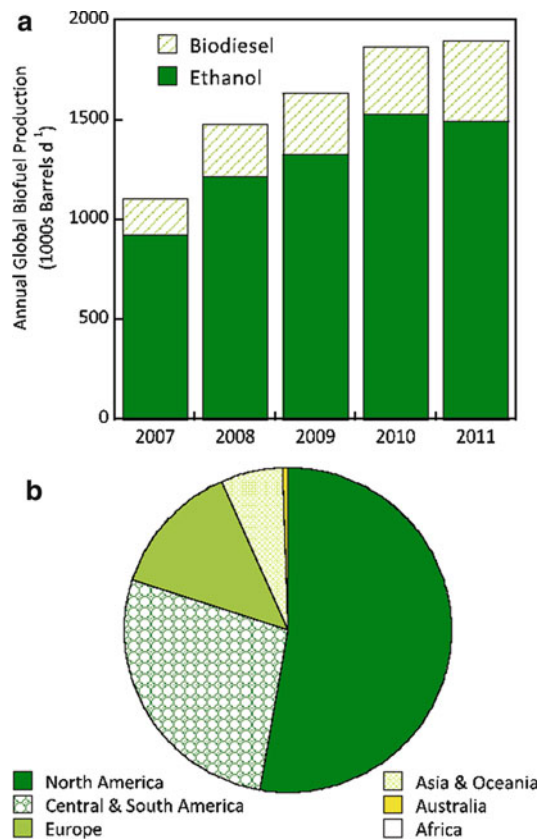


Fig. 1 (a) Annual global liquid cellulosic biofuel production from 2007 to 2011. Total annual production increased 71 % globally across this period. (b) Proportion of total biofuel production by continent from 2007 to 2011. North America produces the most biofuel mostly due to the use of maize for ethanol production to be used in blended fuels (Source: *International Energy Agency*)

Biomass Energy

Plants use solar radiation, carbon dioxide, water, and mineral nutrients to convert solar energy into chemical energy through the process of photosynthesis. In plants, this energy is stored primarily in the form of soluble and non-soluble carbohydrates that drive metabolic activity and form tissue structures, respectively. When carbohydrate bonds are broken via industrial conversion technologies, the energy released can be captured and used as a source of fuel for human consumption. If combusted, the energy takes the form of heat and can be used to produce electricity. If chemically converted to liquid hydrocarbons, the energy remains in a chemical form that can fuel combustion engines. In these processes, the plant tissue is referred to as *biomass*. Biomass has been a steady and reliable source of heat throughout human history and remains so in some developing nations where biomass-generated heat comprises up to 90 % of energy consumption. In developed nations, biomass energy delivers a significantly lower (~3–4 %) proportion of the total energy consumed (Demirbas 2009). However, there has been a concerted effort in recent years to increase the contribution of biomass energy to national energy budgets, particularly from advanced cellulosic sources. Currently, the United States leads the world in bioenergy production mainly due to the use of ethanol in blended fuels (Fig. 1). In the next few sections, the technology necessary for the conversion of biomass to liquid cellulosic fuels, the fuel products generated from these processes,

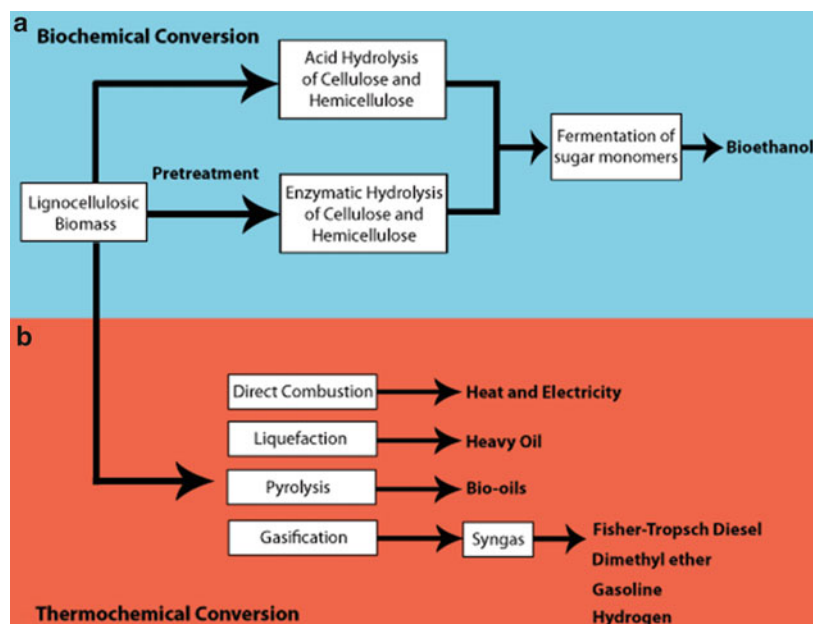


Fig. 2 Primary approaches used to convert lignocellulosic biomass into bioenergy via (a) biochemical and (b) thermochemical conversion processes. Also indicated are the most common fuel derivatives from each process

and the most common plant species used for liquid cellulosic fuel production will be summarized, as will the potential for biomass energy to contribute to the global energy supply in the future.

Biomass Conversion Technologies

Biomass conversion to useful energy forms can be accomplished using a variety of processes. Currently, biochemical conversion and thermochemical conversion techniques are the two main approaches to produce liquid fuels from cellulosic sources (Fig. 2). Many biochemical conversion processes ferment biomass carbohydrates into an alcohol product (bioethanol), while thermochemical conversion heats the raw biomass feedstock in the presence of varying oxygen concentrations to produce thermal energy or a variety of organic molecules. Generally, the method chosen to produce bioenergy depends on the type of biomass feedstock that is used, the requirements for end use, economic conditions, and environmental regulations associated with the energy source. The major fuels currently derived from biomass are biodiesel, methanol, dimethyl ether (DME), syngas, methyl tertiary-butyl ether (MTBE), biomethane from biogas, cellulosic ethanol, and hydrogen. This review will focus primarily on the production procedures used to generate the most widely used of these fuels.

Generation of Liquid Cellulosic Fuels Through Biochemical Conversion

Biochemical conversion of cellulosic biomass to liquid fuel has become an area of intense focus for the scientific and engineering communities in recent years. The primary reasons for this focus relate to the nearly scale-neutral production of fuels as well as the lower costs compared to thermal conversion technologies used in biofuel production. Similar to grain ethanol produced from first-generation sugar and starch crops, bioethanol derived from advanced cellulosic material is produced via fermentation reactions. However, advanced biomass is difficult to process directly into liquid fuel due to the properties of its structural components. Therefore, additional processing steps are required to produce ethanol from cellulosic sources.

Lignin, cellulose, and hemicellulose are the three primary constituents of plant cell walls in cellulosic (i.e., “lignocellulosic”) biomass. These molecules are also found in the greatest abundance in plant tissue and are therefore the main sources of energy derived from cellulosic bioenergy feedstocks. Cellulose microfibrils are large β -1,4 glucan chains that provide the structural framework for the plant cell wall. These macromolecules can be chemically deconstructed into predictable 6-carbon sugars, but due to their complex semicrystalline structure, as well as the insoluble nature of their β -1,4 glucan chains, they are difficult to degrade via hydrolysis (a processing step used in the biochemical conversion of cellulosic biomass to bioethanol). Hemicelluloses are polysaccharides comprised of both pentoses and hexoses. In a plant cell wall, hemicelluloses form hydrogen bonds with cellulose, binding the cellulose microfibrils together and creating a flexible network of macromolecules. Like cellulose, hemicellulose is also difficult to process during the biochemical conversion of biomass to liquid fuel, primarily because the bacterial and yeast species most commonly used to ferment plant sugars do not metabolize the five carbon sugars efficiently. Finally, lignins are large aromatic polymers that form a strong matrix around the cellulose and hemicellulose complex (Taiz and Zeiger 2010). This provides structural support to the plant cell, as well as protection from pests and pathogens. Due to its strength and durability, lignin is resistant to degradation and therefore exists as a by-product during the production of liquid cellulosic biofuels. The removal of lignin, as well as the conversion of complex cellulose and hemicelluloses to simple sugars, is therefore required prior to fermenting cellulosic biomass into ethanol. These initial steps make the processing of advanced feedstocks far more energetically expensive than those required to process first-generation feedstocks.

Four basic steps are required for the biochemical production of liquid cellulosic ethanol: size reduction, pretreatment, hydrolysis, and fermentation. The first, size reduction, is the mechanical reduction of biomass to a smaller size; this facilitates the access of reagents used in the fuel generation process to the array of carbohydrates found in cellulosic biomass. Once the initial feedstock is mechanically processed, the complex lignocellulosic molecules must be broken down into fermentable material via hydrolysis and, depending on the type of hydrolysis used, pretreatment prior to hydrolysis.

Defined generally, hydrolysis is the process of splitting a molecule into smaller fragments with the addition of water. In the biochemical conversion of biomass to liquid biofuel, hydrolysis is used to cleave (depolymerize) complex lignocellulosic polymers (cellulose and hemicellulose) into simple constituent sugar monomers (glucose, pentose, hexose, and xylose) that can subsequently be fermented into ethanol fuel. Hydrolysis of cellulosic biomass can occur chemically or enzymatically. Chemical, or acid hydrolysis, uses an acid (typically sulfuric acid or hydrochloric acid) in the presence of water to break down cellulose into glucose and hemicellulose into pentoses and hexoses. Xyloses can also be produced from hardwood and crop residue feedstocks. Lignin, however, is very resistant to degradation and therefore remains as a by-product in these reactions. Additional toxic by-products, such as hydrolyzates, may also form during this process.

Although acid hydrolysis does not require pretreatment beyond the mechanical processing of the raw biomass feedstock, this process is costly and energetically expensive because the sugar products must be conditioned before fermentation to remove toxic by-products and also because the acid used for hydrolysis must be recovered. Therefore, enzymatic hydrolysis is the more common process used to depolymerize cellulosic biomass into simple sugars.

If carried out enzymatically (enzymatic hydrolysis), the biomass feedstock must first undergo pretreatment. Pretreatment is the physical, chemical, or enzymatic degradation of biomass that is used to increase enzyme access to cellulose and other polysaccharide components of the biomass feedstock. This typically involves the breakdown of the biomass with the same chemicals used

during acid hydrolysis (sulfuric acid or hydrochloric acid), which results in the partial hydrolysis of the biomass. After the biomass has been pretreated, the remaining material that has not been degraded by the acid can then undergo hydrolysis catalyzed by a mixture of enzymatic compounds. This process requires the use of cellulases, a class of enzymes derived from bacterial or fungal sources.

Following acid or enzymatic hydrolysis, the simple sugars, mostly xylose (derived from woody species) and glucose (derived from non-woody species), are converted to liquid bioethanol fuels through fermentation. Fermentation reactions can occur under aerobic or anaerobic conditions and are driven by many different kinds of microorganisms in nature. In the processing of liquid biofuel from cellulosic biomass, microorganisms use sugar monomers to produce ethanol. Once the enzymatic fermentation steps are complete, distillation and dehydration processes can be used to yield anhydrous bioethanol (90–95 % purity by distillation and >99 % purity by distillation and dehydration) that can then be blended with gasoline for use as a fuel in the transport sector (Saxena et al. 2009).

Generation of Liquid Cellulosic Fuels Through Thermochemical Conversion

The burning of biomass (direct combustion) under aerobic conditions to produce heat is the most basic type of energy derived from plant material and can be used to drive mechanical power or generate electricity. Direct combustion can derive energy from both first-generation and advanced biomass sources. However, more complicated thermochemical conversion processes have also been developed to produce liquid fuels from advanced cellulosic sources. If cellulosic biomass is heated under low oxygen conditions, hydrogen and organic gases are produced that can be further processed into liquid fuels such as Fischer-Tropsch biodiesel, dimethyl ether, or synthetic natural gas. The most common of these processes include gasification, pyrolysis, torrefaction, and liquefaction.

Gasification is the thermal conversion of biomass into a combustible gas mixture known commonly as synthesis gas or syngas. Syngas generally contains CO₂, CO, CH₄, N₂, and H₂ in varying proportions, depending on the feedstock used in the process. The conversion of biomass to syngas begins when biomass feedstocks are combusted at temperatures ranging from 800 °C to 1,000 °C. At these high temperatures, biomass decomposes quickly into the syngas components, as well as solid char and tar residues. Syngas, with the addition of different catalysts, can then be used to produce various fuel products including hydrogen, methanol, ethanol, and dimethyl ether (DME). For example, hydrogen gas can be produced using the water-gas-shift reaction (WGS). During this process, CO from syngas reacts with oxygen from water to produce H₂ and CO₂. The H₂ product can then be used to process other liquid fuels or it can be burned directly to produce electricity. Also produced from syngas are a number of hydrocarbons that can be altered further into waxes or liquid fuels that function similarly to traditional gasoline and diesel fuel. The Fischer-Tropsch process, for instance, is the reaction of CO and H₂ in the presence of a metal catalyst to produce a mixture of liquid hydrocarbons that can be further processed into diesel fuel. Another pathway to generate liquid fuel is the methanol-to-gasoline (MTG) process, where methane industrially converted into methanol via specialized catalysts is then further converted to gasoline. Gasification is a useful conversion technology because it allows diverse feedstocks to be processed similarly despite differences in the chemical composition of the biomass feedstock. The versatility of syngas also makes it an attractive option to process liquid cellulosic fuels. For example, DME may be added directly to diesel fuel with no additional steps required, unlike methanol and ethanol.

Pyrolysis is another thermochemical conversion process used to convert biomass feedstocks into liquid cellulosic fuel. In general, pyrolysis is the decomposition of organic material in an anaerobic

Table 1 Major environmental impacts and considerations for first-generation and advanced cellulosic bioenergy feedstocks

Feedstock type	Example feedstocks	Potential environmental impacts
First generation	Sugar crops	Increased land-use change
	<i>Zea mays</i> (corn)	Increased greenhouse gas emissions
	<i>Saccharum officinarum</i> (sugar cane)	Increased nutrient and chemical usage
		Increased soil erosion and runoff
	Oil crops	Decreased storage of soil organic carbon
	<i>Glycine max</i> (corn)	Increased water-use and impact on water quality
Advanced	<i>Brassica napus</i> (rapeseed)	Decreased wildlife diversity
	Perennial C₄ grasses	Increased land-use change
	<i>Panicum virgatum</i> (switchgrass)	Decreased greenhouse gas emissions
	<i>Miscanthus x giganteus</i>	Decreased nutrient and chemical usage
		Decreased soil erosion and runoff
	Short rotation woody crops	Increased storage of soil organic carbon
	<i>Populus</i> spp. (poplar)	Decreased water-use and impact on water quality
	<i>Salix</i> spp. (willow)	Decreased or increased wildlife diversity
		Increased invasiveness
	Wastes and residues	
	Corn stover	
	Forest residues	
	Municipal solid wastes	

environment that leads to the production of gas, solid carbon-based char, and liquid bio-oil fuel. The ratios of these pyrolysis products largely depend on a number of factors including the reaction temperature, pressure, rate of heating, the length of the reaction time, and the biomass feedstocks utilized at the onset. The process of pyrolysis begins by heating the biomass feedstock to a high temperature (ranging from 200 °C to >1,000 °C, depending on the method). At this point volatile organic compounds, or VOCs, form and leave behind a carbonaceous char, a process known as primary pyrolysis. The release of VOCs results in a transfer of heat from the hot VOCs to the feedstock that has yet to be pyrolysed. As the VOCs cool, they form tar. Finally, autocatalytic secondary pyrolysis occurs while primary pyrolysis occurs simultaneously, leading to the production of liquid biofuel. Currently, three types of pyrolysis reactions exist to produce char, tar, and liquid cellulosic fuels. The first is known as *slow pyrolysis*. The slow rate of heating in slow pyrolysis produces a higher ratio of char than liquid and gas products. The second, *fast pyrolysis*, involves fast heating rates and results in a much higher ratio of liquid cellulosic fuels. Finally, *flash pyrolysis* is a more efficient mechanism similar to fast pyrolysis except that very high reaction temperatures and very high heating rates of the reactions are used. Due to the extremely fast heating in flash pyrolysis, the conversion of biomass feedstocks to fuel is much more efficient and leads to a fuel product that does not require further refinement after the initial pyrolytic reactions have occurred.

An additional thermochemical conversion process of biomass feedstocks to liquid cellulosic fuels is known as liquefaction. Liquefaction is the process of heating biomass feedstocks to low temperatures under high pressure with the addition of a catalyst, solvent, and/or reducing gas such as hydrogen to produce a highly viscous insoluble oil that can be used for a variety of purposes. At this time, there is low interest in liquefaction as a viable thermoconversion process because of the

complexity and expense associated with building reactors when compared to other thermoconversion processes like gasification and pyrolysis.

Finally, it should be noted that the physical properties of cellulosic plant material can often complicate thermochemical conversion processes. For instance, the high water and oxygen content of the plant material can produce large quantities of smoke during combustion, while the fibrous nature of its lignocellulosic cell walls can make the biomass physically difficult to process. Recent advancements therefore recommend pretreating the biomass to increase the quality of the biomass and to reduce undesirable side effects associated with fuel production. Torrefaction is a pretreatment method that is similar to pyrolysis but occurs at much lower temperatures (200–300 °C). This process removes oxygen from the plant tissue and decreases the volume of the tissue by as much as 62–69 %. In doing so, the energy content of the biomass is maintained because the material dries and partially de-volatilizes. This reduction in biomass and concomitant energy preservation can increase the energetic density of the material by approximately 20–30 %, which not only makes the material easier to process but also aids in transportation (Bhagwan Goyal et al. 2009).

Bioenergy Feedstocks

The plant species that can be grown as cellulosic bioenergy crops are even more diverse than the processing technologies used to produce biofuels (Table 1). Many crops and wild plant species are currently being used as bioenergy feedstocks, are in development to be used to produce biofuel, or are excellent candidates for biofuel production in the future. Examples of such feedstock plants are agricultural wastes, trees wastes and residues, food crops, and perennial grasses. Generally, these plant species are classified into two categories: food crops and bioenergy crops. Plant species associated with each of these groups present unique challenges in the production of suitable biomass for liquid cellulosic fuel manufacturing and also have varying environmental concerns linked to their growth. A number of characteristics need to be considered when deciding which species to use as a feedstock, including mineral content, moisture content, nutrient and water requirements, dry matter production per unit land area, and the chemical composition of the tissue, especially lignin, hemicellulose, and cellulose content. Furthermore, the geographical distribution of the plant species, the effects of the species on the environment and ecology of the local ecosystem, their response to environmental conditions, their genetic diversity, and other agronomic considerations must be taken into account.

First-Generation Bioenergy Feedstocks

Food crops have long been viewed as the least desirable for use as biofuel feedstock and are often termed first-generation biofuel feedstocks. Among the biggest concerns regarding the use of food crops for biofuels is the tremendous pressure that alternative uses place on an already marginal food supply. Another negative consideration is that most of these crops have an annual lifecycle that require them to be replanted each year, which leads to increased uses of energy for planting as well as pesticide and fertilizer use. For example, of all the plant species used for biofuel production, corn cultivation produces the greatest greenhouse gas emissions. Despite this, corn recently became the largest contributor to bioethanol production. Although corn is now the leading biomass feedstock globally, sugarcane is likely to be a significant contributor in the foreseeable future. Of the food crops used for biofuel production, sugarcane produces yields of up to 100 t/ha with little fertilizer input, thus resulting in a significantly higher energy transfer efficiency than corn. Sugarcane is already produced in significant quantities in South America and remains one of the most important crops globally. In sugarcane, sucrose accounts for 20 % of the dry matter produced and can be quickly converted to bioethanol. After the initial processing of soluble sugars to bioethanol,

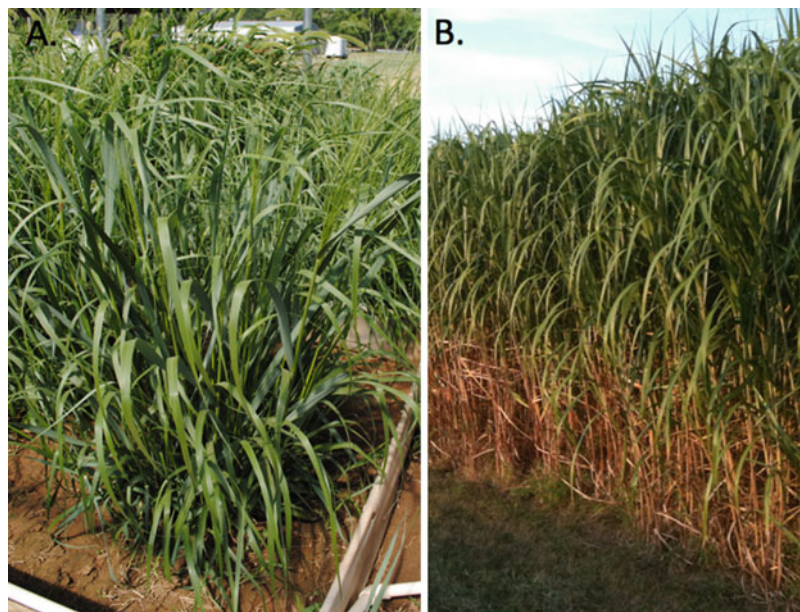


Fig. 3 *Panicum virgatum* L. (a) and *Miscanthus gigantea* (b), two species of grass with a high potential to become important feedstocks for second-generation biofuels (Photo credit: Kimberly O’Keefe (a) and Sarah Davis (b))

a by-product known as bagasse is produced. As conversion technologies of lignocellulose to ethanol continue to improve, sugarcane bagasse is likely to increase in use as biofuel feedstock thus making sugarcane an even stronger candidate for bioethanol conversion (Perlack et al. 2005).

Advanced Bioenergy Feedstocks

Dedicated herbaceous bioenergy (nonfood) crops represent the next wave of biomass feedstocks for biofuel production and are also known as advanced biomass feedstocks. These biomass crops present major advantages over first-generation biomass feedstocks because of their long-term environmental sustainability. Of all of the potential energy crops, the two with the most promise in the future for temperate regions are the perennial rhizomatous grasses, switchgrass and miscanthus (*Miscanthus x giganteus* Greef et Deuter). Switchgrass (*Panicum virgatum* L.) is a warm-season, C₄ perennial grass that is native to North America and adapted to thrive in a wide range of environmental conditions (Fig. 3). Chosen as a model bioenergy species by the United States Herbaceous Energy Crops Program in the early 1990s, switchgrass has been the focus of research as a biomass feedstock for bioethanol production for a number of years. Switchgrass has many cultivars already developed for use as a forage stock, bioenergy crop, and as a restoration species. Switchgrass yields an average of 12 t/ha with recent increases in productivity of ~50 % over the last two decades because of cultivar improvements and agronomic technologies (Field et al. 2008). This total is still far below the productivity of the first-generation biomass feedstock sugarcane, but not always below the yields generated by corn. However, its extensive root system, low-nutrient and water requirements, and perennial lifecycle make switchgrass an attractive option as a biomass feedstock for conversion to bioethanol. In addition, the loss of biomass during harvest is low for switchgrass. Also increasing the attractiveness of switchgrass as a biomass feedstock are the genetic tools, such as linkage maps, that have been developed in recent years for use in breeding programs, an effort that results from the intense focus on switchgrass by the United States Department of Energy (Perlack et al. 2005).

Miscanthus x giganteus is another intensely researched option for biofuel production. *Miscanthus x giganteus* is also a rhizomatous, C₄ perennial grass that is a sterile hybrid of *Miscanthus saccharifloris* and *Miscanthus sinensis*, both native to Asia. Currently a single sterile hybrid, *Miscanthus x giganteus* Greef et Deuter, is the cultivar primarily studied for biofuel production. Like switchgrass, *Miscanthus x giganteus* produces a large aboveground component and stores much of its nutrients belowground in rhizomes prior to harvesting, thus reducing the nutrient requirements for the species. In fact, a number of studies have found *Miscanthus x giganteus* productivity to largely be unresponsive to nitrogen additions. Also like switchgrass, *Miscanthus x giganteus* has been successfully grown in a number of locations globally and therefore represents a single product for conversion technologies to use as a biomass feedstock. *Miscanthus x giganteus* is generally more productive than switchgrass, yielding 25–30 t/ha annually, but can also have greater loss of biomass at harvest than switchgrass. One major unknown for *Miscanthus x giganteus* productivity that requires additional research is the effect of environmental conditions on the productivity of the species. Other challenges presented by *Miscanthus x giganteus* as a biomass feedstock are related to the self-incompatible nature of the species. This self-incompatibility has made genetic research on the species challenging and has hampered genetic improvements to date (but this also what eliminates the invasion risk of *Miscanthus x giganteus*). Recently, a low-density genetic map has been produced for *Miscanthus x giganteus* and has resulted in some genetic studies aimed at the heritability of select agronomic characteristics.

Other advanced dedicated bioenergy feedstocks that are currently under development are woody plant species such as *Populus* spp. (poplar) and *Salix* spp. (willow), also known as short-rotation woody crops (SRWCs). Of the woody plant species being considered for use as a biofuel feedstock, hybrid poplar received the most attention because it has the potential to yield biomass for conversion at a high rate. For example, yields of poplar are estimated between 12.4 t/ha on nonirrigated and unfertilized land to 22.5 t/ha on land that has been irrigated and fertilized. Poplar is also attractive because a number of genomic and genetic tools such as a fully sequenced genome are available for use by the existing research community. However, major setbacks associated with the use of poplar as a biofuel feedstock is the long generation time of the plant as well as the long-term sustainability of yields under low nitrogen inputs to the soil. Engineering the species for increased yields and decreased nitrogen requirements will therefore be important steps in developing poplar as a sustainable alternative energy solution. These improvements have the potential to also enhance production for the timber and paper industries as well (Field et al. 2008).

Finally, a readily available cellulosic feedstock can be gathered from agricultural waste products. Agricultural wastes include corn stover (the leaves and stalks of the corn crop), sugarcane residues, and rice hulls, as well as a number of other agricultural residues. Because of the inefficiencies that exist in current conventional agriculture production, these waste products remain among the most important feedstocks for biofuel production. In addition, the use of agricultural wastes is generally thought to be a better option for biofuel production than food crops such as corn because these waste products are the by-products of existing agricultural activity. This reduces the energy requirement needed for production as well as the use of pesticides, fertilizers, and water. In many cases, if agricultural wastes are not used for biofuel production, they are either burned or disposed in a landfill, both of which can have a higher environmental impact than the production of biofuel. Additionally, forest residues from logging, as well as municipal wastes, also have the potential to be used as cellulosic bioenergy feedstocks.

The Case for Liquid Biofuels in the World Energy Market

As world energy demands, as well as the negative impacts of fossil fuel combustion on the natural environment, human health, and global economies continue to increase, the case for liquid fuels produced from sustainable sources becomes stronger. Many factors contribute to this reality. First, because of the wide geographic ranges of the biomass feedstocks described above, biofuels present an opportunity for increased domestic energy production. This new area for domestic energy production also creates a unique opportunity for economies to further develop agricultural industries and buildup rural communities. In addition to providing energy security, biofuels have the ability to decrease greenhouse gas emissions by reducing the use of fossil fuels while simultaneously increasing the potential for long-term sequestration of atmospheric carbon dioxide in plant tissues and soils.

Another attractive feature of liquid biofuels is the amount of energy, especially in the transportation sector, that they can generate currently and in the future. The earth receives annually $\sim 3.8 \times 10^6$ exajoules ($1 \text{ EJ} = 10^{18} \text{ J}$) of solar energy. This is such an extraordinary amount of energy that it meets the total global annual energy demand (450 EJ year^{-1}) in 1 h of daylight. Globally, plants fix many times more ($\sim 2,900 \text{ EJ year}^{-1}$) than the total annual global energy demand by converting this solar energy into standing biomass through photosynthesis, a term known as net primary productivity (NPP). Unfortunately, not all of this energy is available for use as bioenergy feedstocks on a sustainable basis. Of this total, a number of estimates have placed the total energy potential from sustainable biomass feedstocks at $100\text{--}300 \text{ EJ year}^{-1}$. Currently, only $40\text{--}55 \text{ EJ year}^{-1}$ of energy is produced from biomass globally. Because of the significant potential for much higher proportions, a number of developed nations have committed to significantly increasing the amount of bioenergy used by the year 2050. The Intergovernmental Panel on Climate Change estimates that by the year 2050 global energy demand will increase to $\sim 560 \text{ EJ year}^{-1}$. Currently, the energy generated from biomass has the potential to meet 32 % (180 EJ year^{-1}) of the future global energy demand laid out by the IPCC. This proportion is projected to increase to 46 % (325 EJ year^{-1}) by 2100. While the use of energy derived from biomass has the potential to change the global energy portfolio, there are a number of pressing environmental and sustainability considerations that must be accounted for now and in the future (Field et al. 2008).

Ecological Considerations Associated with Cellulosic Biofuel Production

Management Decisions

Cellulosic bioenergy crops are generally associated with fewer negative ecological consequences than first-generation bioenergy feedstocks and may even provide many benefits to the environment. Because these crops are highly productive, have extensive root systems, require few water and nutrient inputs, and can be grown for many years without requiring replanting, cellulosic bioenergy feedstocks may reduce greenhouse gas emissions, sequester soil organic carbon, improve soil and water quality, and create wildlife habitat. However, the extent to which cellulosic bioenergy production will impact the environment will depend on the crops used, the land-use changes associated with them, and how these crops are managed. If managed poorly, their production may not provide any ecological benefits over first-generation bioenergy crops and may even adversely impact the environment. When evaluating the ecological consequences associated with cellulosic bioenergy production, the following factors should be considered.

Land-Use Change

Bioenergy production on a scale large enough to meet current energy needs will require substantial areas of land provided via some form of land-use change (LUC) (Davis et al. 2011a, b). Land-use changes can directly alter existing land (e.g., agricultural land used previously for the production of other crops, natural ecosystems converted to agricultural land, or marginal land that is degraded from extensive agricultural practice and is unsuitable for further food crop production). Bioenergy cultivation can also indirectly induce land-use changes (i.e., indirect land-use change, iLUC), when uncultivated land is altered to produce a crop that was displaced by bioenergy feedstock cultivation on current agricultural land. For instance, in a hypothetical scenario where biofuel production replaces wheat production on a farm, the farmer may convert a native ecosystem in another area to compensate for the lost wheat production in the original location.

When addressing iLUC, it is important to note that tracking and predicting the many variables associated with iLUC is extremely difficult and associated with large uncertainty. Some agencies, such as the United States Environmental Protection Agency (EPA), have tried to evaluate effects of iLUC using models, but the models produce results with large variance because accounting for all associated variables can be difficult (Davis et al. 2011a). Although estimating the effects of iLUC is difficult, most models indicate that there are unintended consequences of biofuel policies for land use that should be addressed. Because iLUC has the potential to be counterproductive to mitigating climate change (through the development of uncultivated land), awareness of this potential consequence is key for policy makers to place regionally appropriate constraints on biofuel development.

Evidence is mounting that integrated land management policies might reduce unintended consequences for LUC and iLUC (Davis et al. 2011a). As discussed previously, many opportunities exist to coproduce biofuels and other resources, reducing the need for additional land. Wastes from many industries could serve as biofuel feedstocks, including residues from the timbering, paper, wood products, building, and agricultural industries. However, opportunities for integrated land management are often regionally specific and cannot be generalized globally for similar industries.

Crop Management

Various management decisions associated with annual first-generation biofuel crop production, such as planting, harvesting, and tilling methods, can also determine the environmental impact of a bioenergy crop (Howarth and Bringezu 2009). For example, bioenergy crops can be planted as monocultures (single-species crop stands) or in mixed assemblages (multiple species are planted in crop stands). They can also be planted in crop rotations, where different crops are planted and harvested on a rotational schedule (e.g., crop A is grown and harvested for 5 years and then crop B is grown and harvested for 5 years). The timing and pattern of crop harvest can also vary. Crops can be harvested annually, more than once per growing season, or less than once per growing season. The entire crop stand can be harvested at once, or alternatively, only sections of the stand can be harvested at once (i.e., strip harvesting). Crops can be harvested during different seasons. Finally, agricultural soil can be tilled, or mechanically disturbed to facilitate crop planting, in a variety of ways. Intensive tillage methods leave few crop residues, whereas less intensive, or reduced, tillage methods leave greater amounts of crop residues. No-till strategies do not till agricultural soil prior to planting, which leaves crop residues undisturbed. Strip-till methods only disturb the soil directly where the crop is planted, leaving strips of untilled soil between. Rotational tillage only tills the soil at particular intervals (i.e., every other year). Variation in any of these factors will ultimately influence the degree to which cellulosic bioenergy crops affect greenhouse gas emissions, soil properties, soil and water quality, and wildlife.

Greenhouse Gas Emissions

Greenhouse gases are chemical compounds that absorb infrared radiation and trap heat in the atmosphere. Although this “greenhouse effect” is a naturally occurring process and is responsible for warming the planet by about 33 °C, human activities such as deforestation and fossil fuel combustion have increased the concentrations of many greenhouse gases in the atmosphere, which has further increased the temperature of the earth in recent years and driven other phenomena associated with global climate change (Schlesinger and Bernhardt 2013). Common greenhouse gases include carbon dioxide (CO₂), water vapor, and other trace gases such as methane (CH₄), nitrous oxide (N₂O), tropospheric ozone (O₃), and chlorofluorocarbons (CFCs). These gases are relatively inert so they remain in the troposphere (the lower atmosphere) for a long time and have greater potential to absorb more radiation over time compared to more reactive, short-lived gases. Thus, greenhouse gases can have long-lasting consequences on atmospheric chemistry and global climate once released into the troposphere by human activities such as fossil fuel combustion and land-use change.

Bioenergy feedstocks have the potential to mitigate global climate change phenomena because they act as carbon sinks by sequestering atmospheric CO₂ as they grow and because they can offset anthropogenic greenhouse gas emissions by slowing fossil fuel exploitation (Williams et al. 2009). However, land-use conversion and management practices associated with crop cultivation can also release greenhouse gases that may reduce or in some cases completely eliminate bioenergy potential to offset anthropogenic greenhouse gas emissions. For instance, bioenergy feedstock cultivation requires land, which usually involves a land-use change that reduces soil organic carbon (SOC) and releases CO₂ into the atmosphere (see section “[Soil Organic Carbon](#)”). The magnitude of CO₂ release, however, depends on the type of land-use change used to cultivate the bioenergy crop. Land-use changes release more CO₂ if highly productive land, such as a forest ecosystem, is converted to a bioenergy crop field than if the conversion occurs on agricultural land or marginal land (a low productivity ecosystem) (Davis et al. 2011b). The bioenergy feedstock chosen for cultivation can also determine the impact of bioenergy production on greenhouse gas emissions over time. Perennial grasses, for instance, can grow for many years without the need to till and replant, resulting in greater accumulation of SOC relative to an annual cropping system (Blanco-Canqui 2010). Increased SOC sequestration in dedicated herbaceous bioenergy crops relative to first-generation bioenergy crops can therefore create a net greenhouse gas sink if this perennial system replaces annual corn agriculture. A popular metric that is used to determine if land-use change results in positive or negative consequences for ecosystem services is the payback time needed to neutralize the carbon debt incurred through soil disturbance and the removal of vegetation from the landscape (Davis et al. 2011a). The payback time is dependent on the original condition of the land (e.g., soil, aboveground plant community, management history), climate, and the rate at which the biofuel agroecosystem sequesters carbon.

Bioenergy production can also release N₂O emissions if substantial fertilizer inputs are used to grow the crop. Fertilizers add nitrogen to the soil in the form of ammonium (NH₄⁺), which can increase rates of microbial nitrification and denitrification in the soil and subsequently produce gaseous nitric oxide (NO) and N₂O as by-products (Schlesinger and Bernhardt 2013). N₂O is highly inert and has a long residence time in the atmosphere, so it has great potential to warm the atmosphere over time (about 300× greater than atmospheric CO₂). N₂O also breaks down into NO when exposed to ultraviolet radiation in the stratosphere, which can promote stratospheric ozone destruction and subsequently increase the amount of harmful solar radiation that reaches the surface of the planet. Therefore, N₂O production associated with agricultural activities can have wide-ranging consequences for atmospheric chemistry and climate. Cellulosic feedstocks are generally

less likely to produce N₂O emissions than first-generation bioenergy crops because dedicated herbaceous bioenergy crops are often characterized by high nutrient-use efficiency and can sometimes be grown without the addition of nitrogen fertilizer (see section “[Nutrient and Chemical Inputs](#)”) (Williams et al. 2009). Low nitrogen inputs reduce rates of nitrification and denitrification in the soil, which can ultimately reduce N₂O emissions. Dedicated herbaceous bioenergy crops can also be grown under drier conditions than traditional row crop monocultures, which may reduce rates of denitrification and reduce N₂O emissions compared to first-generation bioenergy crops. However, soil disturbance associated with land conversion can also accelerate nitrogen cycling processes, which may increase N₂O emissions associated with the establishment of a dedicated herbaceous bioenergy crop despite their low-nutrient requirements. Therefore, bioenergy feedstock, land-use, and crop management must all be considered when assessing the impact of biofuel production on terrestrial N₂O emissions.

Soil and Nutrient Management

Many of the land-use changes and management strategies used to cultivate first-generation bioenergy crops can impact soil properties such as soil hydraulics, soil chemistry, and soil biodiversity. These crops are tilled often and require vast water and nutrient inputs, which reduces soil porosity, nutrient quality, water-holding capacity, and microbial activity, ultimately reducing soil productivity and exacerbating erosional processes. The biological characteristics and management requirements of cellulosic bioenergy feedstocks, however, have the potential to improve the biological, chemical, and physical properties of soils. These crops are highly productive, have extensive root systems that penetrate deep into the soil profile, and require few water and nutrient inputs, which can improve soil aggregation, soil hydraulic conductivity, soil water infiltration, water retention, soil organic matter, and nutrient retention. Perennial bioenergy crops therefore have great potential to improve degraded soils, although the degree to which these feedstocks can improve soil properties depends on the crop used, where the crop is grown, and how the crop is managed.

Soil Erosion and Runoff

Surface runoff is the movement of water across a land surface (typically soil) that occurs when the soil is saturated or when the rate of precipitation is greater than the rate of water infiltration in the soil. Runoff can result in soil erosion, the transport of soil materials (i.e., nutrients, organic material, or contaminants) by some natural process (such as water or wind movement) to a different location. Runoff and soil erosion typically occur in agricultural systems when soil is harvested or disturbed so that biomass cover is reduced and/or the soil is compacted (U.S. Congress Office of Technology Assessment 1993). When biomass cover is reduced, a greater proportion of rainfall hits exposed soil, which dislodges particulate matter and washes nutrients and organic matter away from the upper soil layers. Runoff also occurs when soil becomes compacted because soil porosity (the amount of “empty” spaces in the soil) and water infiltration are reduced, increasing the rate of soil saturation. This can negatively impact agricultural systems because the loss of soil nutrients and organic matter associated with erosion reduces soil productivity and plant growth.

Runoff and erosion are often associated with the cultivation of annual row crops because these crops do not produce dense stands and also because they are managed extensively with large equipment during planting and harvesting each year. However, dedicated herbaceous bioenergy crops have the potential to reduce runoff and soil erosion rates (Lemus and Lal 2005). Perennial C₄ grasses, in particular, are high yielding and produce dense stands that intercept large quantities of rainfall, reducing the amount of water that directly hits the soil. Additionally, dense stands and the litter layers associated with them can reduce wind erosion. These species also have extensive root

systems that decrease soil compaction, promote soil aggregation, and increase soil porosity, which can increase the amount of water that permeates deep soil layers. Finally, many perennial crops are replanted infrequently with some species only replanted every 15–20 years, which reduces the degree of management by heavy equipment and thus reduces the risk of soil compaction. Reduced erosion can benefit agricultural and natural systems by maintaining soil structure, retaining soil organic matter and nutrients, and reducing the transport of undesirable nutrients and/or contaminants to other natural systems (e.g., nutrient deposition and in aquatic systems).

The degree to which cellulosic bioenergy crops reduce soil erosion depends on the crop used and how the crop is managed (Williams et al. 2009). Runoff and erosion are generally reduced by perennial C_4 grasses and short-rotation woody crops. Conversely, harvesting annual crop residues such as corn stover may actually exacerbate the rate of surface runoff and soil erosion in an agricultural system because residue removal exposes soil to wind and rainfall and the heavy equipment used to remove the residues can compact the soil. Harvesting the crop during the winter or when the soil is dry can however reduce soil compaction. Minimum or no-till farming, as well as contour plowing (plowing along the landscape's elevation contour to form furrows that capture water), can also reduce surface runoff and erosion. Cellulosic bioenergy crops that are managed more intensely (i.e., are harvested multiple times throughout the year or are extensively tilled) can also counteract the benefits of perennial grasses on soil structure. The degree to which soil erosion is reduced by cellulosic bioenergy crops can depend on the type of soil in which the crop is growing, as well as on the length of time following establishment. Perennial C_4 grasses, for instance, may not reduce erosion in the first year they are planted. In fact, these crops may not improve soil structure or soil hydraulic properties for many years after they are established (Howarth and Bringezu 2009). Therefore, cellulosic bioenergy crops do have the potential to reduce surface runoff and soil erosion, although this depends on crop management and may take decades.

Nutrient and Chemical Inputs

Cellulosic bioenergy crops, particularly dedicated herbaceous bioenergy crops, can potentially benefit soil nutrients and nutrient cycling processes. Some perennial C_4 grasses have low-nutrient requirements and high nutrient-use efficiency (i.e., they produce more biomass per fewer units of essential nutrients such as nitrogen or phosphorous); thus, they require little fertilizer inputs and can be grown on degraded, marginal soils (Carroll and Somerville 2009). These crops also require less herbicide and pesticide inputs than annual row crops, particularly because these chemicals are only applied in the first year of establishment and because these perennial crops are grown for many years (U.S. Congress Office of Technology Assessment 1993). Nutrients and chemicals are also better retained in the soil by dedicated herbaceous bioenergy crops because the organic material added to the soil by highly productive perennial C_4 grasses provides a surface to which nutrients can adhere and because perennial roots retain nutrients between growing seasons. This has the potential to enhance crop productivity, as well as the productivity and diversity of soil microorganisms. However, these benefits are primarily associated with perennial C_4 grasses and short-rotation woody crops; annual crop residue removal actually reduces essential plant nutrients from the soil and degrades soil quality.

The low chemical inputs required for cellulosic bioenergy crop cultivation can provide several benefits to the environment. First, low fertilizer inputs can greatly reduce energy consumption because the production of industrial nitrogen fertilizer (i.e., industrial nitrogen fixation via the Haber-Bosch process) is an energetically expensive process. Second, low fertilizer, herbicide, and pesticide inputs can improve soil quality and reduce the amount of chemicals that are present in surface runoff, thus reducing rates of nitrification and denitrification (see [Greenhouse Gases](#)) and

harmful ecological processes such as nitrogen leaching and eutrophication (see section “[Water Quality](#)”). Low fertilizer inputs, for example, can reduce nitrogen leaching in the soil by reducing rates of nitrification. Nitrification is the two-step process by which aerobic chemoautotrophs oxidize ammonium (NH_4^+) to nitrite (NO_2^-) and then nitrate (NO_3^-), a highly soluble form of nitrogen (Schlesinger and Bernhardt 2013). Increasing NH_4^+ inputs to a system via fertilization increases rates of nitrification and ultimately increases the concentration of soluble NO_3^- that can leach through the soil and contaminate groundwater. Thus, bioenergy crops that require low nitrogen inputs will reduce NO_3^- leaching associated with agricultural practices. Proper management regimes have the potential to enhance these environmental benefits. For instance, more nutrients can be retained in the soil by harvesting biomass after plant senescence, when nutrients have been translocated belowground to roots. Planting crop stands in mixed assemblages with nitrogen-fixing plant species interspersed among the biomass crop may also reduce the need for additional nitrogen input.

Soil Organic Carbon

Soil organic carbon (SOC) is ecologically important in the global carbon cycle. This soil reservoir of organic residues contains approximately 1,500 Pg carbon, almost twice the amount of carbon contained in the atmosphere (approximately 780 Pg) and three times the amount stored in terrestrial biota (approximately 500 Pg) (Schlesinger and Bernhardt 2013). Thus, changes in the amount of carbon stored in soil, particularly reductions in SOC, can greatly impact other carbon cycling processes. Carbon lost from the soil primarily returns back to the atmosphere through heterotrophic respiration, which can have cascading effects on carbon fluxes between other carbon pools (e.g., atmosphere–ocean CO_2 exchange). Reductions of SOC can also impact terrestrial systems by decreasing plant productivity, degrading soil quality, and decreasing water retention. SOC loss is caused by a variety of factors including soil erosion, root biomass reduction, or soil disturbances that increase decomposition rates and microbial respiration via increases in soil aeration and temperature (Lemus and Lal 2005). Although this is a naturally occurring process, intense agricultural management and land-use changes that convert natural ecosystems to agricultural land greatly increase the amount of carbon that is lost from the soil.

Perennial feedstocks have the potential to mitigate SOC losses associated with land-use changes by sequestering atmospheric CO_2 and adding substantial amounts of organic material back to the soil carbon pool (Lemus and Lal 2005). For instance, the high yields associated with dedicated herbaceous bioenergy crops return organic carbon back to the soil in the form of aboveground residues and root dieback. The extensive root systems produced by these crops also grow deep into the soil profile, which transfers organic carbon to deep soil layers where SOC decomposition rates are low. Thus, carbon inputs to the soil may be larger than carbon outputs, increasing SOC over time. Increasing SOC is highly beneficial in an agricultural system; higher SOC levels can improve soil structure, buffer soil acidity, increase crop quality and productivity, increase the abundance of soil microorganisms, reduce runoff, and improve water quality (U.S. Congress Office of Technology Assessment 1993). However, the amount of SOC that bioenergy crops can add to a system depends on a variety of factors, including soil type, climate, and land management. The amount of carbon that feedstocks can sequester and add to the soil also depends on the amount of carbon already present in the soil because soil can eventually become saturated with carbon. Although absolute limits are debated, greater amounts of carbon can be added to degraded soil that is carbon-depleted than highly productive soil that is closer to its carbon saturation point (Blanco-Canqui 2010). These crops therefore have greater potential to improve marginal lands compared to more productive lands. The amount of organic carbon that is added to the soil by bioenergy crops depends on the crop used and

the way the crop is managed. Perennial C_4 grasses and short-rotation woody crops tend to increase SOC, but removing annual crop or forest residues actually decreases SOC by directly removing organic material from the soil and by exposing the soil to higher air temperatures that increase rates of organic material decomposition (Lemus and Lal 2005; Williams et al. 2009). Greater amounts of SOC are also retained in the soil when crops are harvested less frequently and minimum or no-till farming regimens are used.

Water

Water Requirements

Agricultural crops, including food crops and first-generation bioenergy crops, can be characterized by low water-use efficiency (they assimilate less carbon per unit water transpired) and are sometimes irrigated with water collected from lakes, rivers, and groundwater to produce higher yields. This can have negative socioeconomic and environmental consequences because irrigation aggravates water shortages and reduces surface water flow necessary for wetland ecosystems and aquatic biota. Many dedicated herbaceous bioenergy crops can produce high yields without irrigation because these perennial grasses utilize the C_4 photosynthetic pathway and use water more efficiently than plants that utilize the C_3 photosynthetic pathway (Carroll and Somerville 2009; Williams et al. 2009). In addition, many perennial bioenergy feedstocks have extensive deep root systems that aid in retaining water in the soil more than the small root systems associated with annual row crops, further reducing the need for irrigation (Howarth and Bringezu 2009). Because they do not require as much irrigation, cellulosic bioenergy feedstocks compete less with food crops for water and are also less likely to impact aquatic systems than first-generation bioenergy crops. There are some other considerations to be accounted for in water-use of biofuel species, including the length of growing season that may substantially increase the water needs across the growing season. Finally, these crops do require some additional water for chemical processing; however, they do not require greater amounts than processing first-generation bioenergy crops.

Water Quality

Cellulosic bioenergy feedstocks can also improve water quality relative to annual row crops. These crops do not require substantial chemical inputs, and their extensive root systems, as well as their ample SOC inputs, reduce surface runoff and soil erosion. This can decrease chemical contamination of aquatic habitats and can subsequently reduce nitrogen leaching (see section “[Nutrient and Chemical Inputs](#)”) and aquatic eutrophication (i.e., aquatic ecosystem responses to nutrient additions). Thus, these feedstocks are less associated with negative aquatic processes such as phytoplankton or algal blooms and hypoxic conditions (oxygen depletion) than annual crops (Blanco-Canqui 2010).

Impacts on Wildlife and Biodiversity

Land-use changes associated with bioenergy production will likely affect various aspects of biodiversity including the number of species in a given habitat (species richness) and/or the relative abundance of each species in a given habitat (species evenness), which can potentially have cascading consequences on other biological processes at the community and ecosystem scales. Generally, land-use changes that convert natural ecosystems to agricultural land result in habitat loss and habitat fragmentation, which can ultimately reduce species richness and alter species evenness (Dauber et al. 2010). Cellulosic bioenergy crops that directly or indirectly displace natural habitat can therefore negatively impact wildlife and biodiversity. If planted on marginal lands, these crops may have neutral or even positive impacts on wildlife. Perennial grasses such as switchgrass and

Miscanthus x giganteus can improve the quality of degraded habitats and create an environment that structurally resembles a natural grassland ecosystem, which can provide nesting and foraging habitat for many birds and small mammals (Williams et al. 2009). These high-yielding grasses also produce large amounts of litter and are seldom tilled, which provides substantial, undisturbed cover for ground-dwelling species.

However, wildlife benefits from cellulosic bioenergy cultivation will only occur if the feedstock is managed correctly. Perennial grasses planted in monoculture may actually reduce wildlife biodiversity if the crop system replaces a high productivity ecosystem because monoculture fields decrease environmental heterogeneity and reduce the number of species that can occupy an area (U.S. Congress Office of Technology Assessment 1993). Switchgrass monocultures, for instance, primarily provide habitat for grassland birds that favor tallgrasses (although birds that prefer less cover may become more abundant following harvesting). Conversely, crops grown in mixed assemblages (i.e., two to three species) can enhance landscape heterogeneity and create a more diverse environmental mosaic that can support more species in a given area. Harvesting strategies may also affect the degree to which bioenergy crops impact biodiversity (Fargione et al. 2009). Frequent harvests (>1 harvest per year) may favor species that prefer a short-grass habitat, while infrequent harvests may favor species that prefer tallgrasses. Rotational or strip harvesting can improve environmental heterogeneity and support the coexistence of multiple species that prefer different habitats. Crop harvests can also interfere with avian breeding seasons, so harvesting in the autumn or winter, after the breeding season of many bird species has ended, may benefit a variety of bird species (Dauber et al. 2010). However, autumn or winter harvests can reduce ground cover and consequently increase winter mortality for many ground-dwelling birds and mammals. Crop management strategies can therefore have wide-ranging impacts on many wildlife species, and these consequences must be carefully considered when making land management decisions to cultivate cellulosic bioenergy crops.

Other cellulosic bioenergy crops may also impact wildlife and biodiversity. For example, short-rotation woody crops can provide habitat for birds and small mammals, although these habitats are often less suitable than natural forests because crop stands are less complex than naturally occurring forest ecosystems (Dauber et al. 2010). Woody crops may also reduce habitat fragmentation if planted as a corridor to connect separated forest patches. Reduced habitat fragmentation can facilitate the movement of individuals and populations between habitats and is ultimately associated with high biodiversity. Finally, annual crop residues, as well as forest residues, tend to have fewer impacts on biodiversity than short-rotation woody crops or perennial grasses because their collection is not associated with land-use changes that reduce viable habitat or environmental heterogeneity. Residue removal, however, does reduce ground cover for wildlife and also decreases soil nutrients, which may impact the biodiversity of ground-dwelling animals or soil microorganisms. Therefore, the type of bioenergy feedstock used, as well as the strategy used to plant and maintain the crop, can strongly influence the degree to which cellulosic bioenergy cultivation impacts wildlife and biodiversity.

Invasive Species Potential

Bioenergy Crops as Invasive Species

An invasive species is one that occurs in location that is not part of its original (i.e., native or endemic) range. In order to successively invade a new range, a non-native plant must have certain characteristics that enable it to overcome multiple barriers (i.e., physical dispersal barriers, novel environmental conditions, competition with new species, predation by new enemies) (Hierro et al. 2005). Therefore, invasive plants typically have high relative growth rates, high competitive

abilities, high fecundity under optimal conditions, and morphological and/or physical similarity to the native species in its new range.

Interestingly, these characteristics are also those associated with many cellulosic bioenergy crops. Dedicated herbaceous bioenergy crops, for example, are perennial, have rapid growth rates, produce high yields, utilize the C₄ photosynthetic pathway, have high resource-use efficiency, and propagate both vegetatively and by producing a seed crop. These species are also broadly adapted across a wide geographic range and are tolerant of various environmental conditions. For instance, crops such as switchgrass and *Miscanthus x giganteus* are tolerant of drought, as well as flooding, and can grow on low-nutrient, degraded soils. These traits promote efficient seedling establishment and quick production of high yields with relatively little water and nutrient inputs. However, these traits may also promote the undesirable invasion of bioenergy crops into nonagricultural areas, particularly if the crop is cultivated outside of its native range or if the crop is genetically modified to enhance qualities that concomitantly increase invasiveness (Raghu et al. 2006; Williams et al. 2009). Unintentional introduction can occur locally or on larger scales as a result of direct spread from the agricultural land source or by propagule release during harvesting and processing (Fargione et al. 2009). Biomass feedstocks are typically harvested following plant senescence, when seeds have been produced and are still attached to the plant, which can result in seed rain onto roadsides during transportation to biofuel production facilities. These seeds may also contaminate the equipment used to plant or harvest the crop, which may subsequently taint other agricultural crops if the equipment is not properly sterilized.

A non-native bioenergy crop may survive and form persistent populations because it will likely experience a decrease in pressure from specialist enemies (i.e., specialist pathogens and herbivores) when introduced to a new region (Hierro et al. 2005). The non-native species is not typically susceptible to the specialist enemies of the native species in its new range (assuming that these specialist enemies do not switch host preference to the invader) and should therefore experience a decrease in regulation by enemies relative to the native species in the new region. The risk of invasion, however, may decline if native crops or sterile cultivars (such as *Miscanthus x giganteus*) are cultivated, although other traits associated with these species may promote their invasiveness despite their lack of a viable seed crop. Invasiveness is not typically associated with other cellulosic bioenergy sources such as annual crop residues and short-rotation woody crops.

Risk of Invasion by Other Species

Depending on how the crop is planted and maintained, cellulosic bioenergy crops also have the potential to increase the risk of invasion by other species in bioenergy agricultural lands. Dedicated herbaceous bioenergy crops can particularly promote the invasion of other non-native species if the crop is planted as a monoculture. Generally, habitat homogeneity can increase the susceptibility of a location to invasion by non-native species because less diverse communities (communities with fewer species) have more available resource niches compared to more heterogeneous communities, which can be utilized by an introduced species (Hierro et al. 2005). Cultivating bioenergy crops in mixed assemblages, however, may reduce the number of available niches in a community and subsequently reduce this risk of invasion. Growing multiple genotypes of a single species may also increase landscape heterogeneity and reduce invasions by other species. Similarly, other species may become invasive in bioenergy agricultural lands if substantial amounts of water and/or nutrients are added to the crop, which may create more available resource niches that can potentially be utilized. Most cellulosic bioenergy crops, however, do not require substantial water or nutrient inputs, so this risk may actually be lower compared to traditional row crops.

Pests and Pathogens

Cellulosic bioenergy crops can become infected by a variety of pests and pathogens including viruses, bacteria, fungi, insects, molds, and nematodes. Depending on the host and the type of disease, these infections have the potential to reduce photosynthetic rates, impair plant-water relations, decrease reproductive output, and ultimately reduce whole-plant yield and survival. This can significantly reduce the productivity of a crop stand and even impact other agricultural and natural ecosystems if the pathogen is transmitted via insects that can travel long distances. Thus, the interaction between cellulosic bioenergy crops and their pathogens can have significant consequences on both local and larger spatial scales.

The risk of infection by pests and pathogens may be a significant concern for dedicated herbaceous bioenergy crops because bioenergy cultivars can be genetically homogenous and are usually planted in monoculture. Generally, the probability of pathogen transmission between hosts increases with host abundance and distribution (Gonzalez-Hernandez et al. 2009). In natural ecosystems, susceptible hosts often co-occur with other species in a nonuniform distribution, decreasing the likelihood that pathogens will physically transfer from host to another. This probability is considerably higher when many individuals of the same species co-occur in a given area and are spaced uniformly, so herbaceous bioenergy monocultures are particularly vulnerable to the spread of pathogens and pests. Bioenergy cultivars may also be more susceptible to pests and pathogens because breeding programs have selected for certain traits that improve their yield and resistance to adverse environmental conditions (e.g., rapid growth rates, high resource-use efficiency, etc.); in doing so, bioenergy cultivars are somewhat genetically homogenous. This can increase the rate at which a pest or pathogen can adapt to a particular host genotype and will ultimately increase the probability of pathogen spread, as well as pathogen virulence (Gonzalez-Hernandez et al. 2009). Additionally, selecting for high yields may increase a cultivar's susceptibility to infection because plants that allocate more resources to growth typically invest fewer resources to defensive mechanisms (Schrotenboer et al. 2011). Quick-growing perennial grasses, therefore, have the potential to become highly susceptible to detrimental pests and pathogens. Planting bioenergy crops in mixed assemblages to enhance genotypic or species diversity, or even using crop rotations to disrupt the life cycles of many pests and pathogens, may reduce this risk and prevent the spread of disease within a crop stand and between other ecosystems.

Future Directions

Biofuels produced from cellulosic sources have the potential to reduce the need for fossil fuel energy in the future. As mentioned throughout the previous sections, advanced cellulosic crops generally possess many ecological advantages over first-generation feedstocks. Cellulosic bioenergy crops typically have extensive rooting systems and produce high yields without requiring large water or nutrient inputs. These characteristics can increase SOC and reduce rates of greenhouse gas emissions, runoff, and eutrophication. Additionally, perennial cellulosic crops can be cultivated on land considered marginal for agricultural production and improve wildlife habitat quality. However, cellulosic feedstocks are also difficult to process into liquid fuel, and depending on how they are managed, their impact on natural ecosystems may not always be positive. Therefore, the development of cellulosic biofuels for widespread future production requires continued research in areas of feedstock propagation and conversion technologies. Specifically, future work in the development of biofuels from cellulosic sources should aim to improve the conversion of cellulosic biomass to liquid fuel. Genetically engineering bioenergy crop species to make lignocellulosic material easier to

hydrolyze, either by reducing or modifying lignin content, may increase the cost efficiency of liquid biofuel production. Work in the future should also focus on the development of new enzymes that are better able to break down lignocellulosic biomass. Ultimately, these developments will require more research to better understand plant cell wall chemistry. A better understanding of the environmental impacts associated with bioenergy feedstock production is also needed. Bioenergy crops can have various impacts on the environment, depending on the crop used and how the crop is managed, so predicting how bioenergy production will impact various ecosystems in the future can be difficult. This will be especially important in the face of global climate change, as different crops will likely respond differently to changes in atmospheric chemistry and climate. Therefore, if the full benefits of cellulosic bioenergy production are to be realized, a dedication must be made to the production and management of bioenergy feedstocks that not only have few adverse impacts on the environment but that are also more efficient in generating liquid fuels from lignocellulosic material.

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